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CARBONATITES OF THE CHILWA SERIES OF SOUTHERN NYASALAND

By

W. CAMPBELL SMITH

(*With Plate 7*)

INTRODUCTION

When the description of the Chilwa Series was published (Dixey and others, 1937)[1] it was intended that it should be followed by a later publication dealing with the composition of the 'limestones' associated with the 'feldspathic intrusives' and alkaline rocks of Chilwa Island, Tundulu Hill, Kangankunde, and other localities at which the Chilwa Series had been studied by Dr. Frank Dixey and Mr. C. B. Bisset. Owing first to the pressure of other work and then to a long absence during the war and to the subsequent work of reassembling and rearranging the collections in the Natural History Museum after the war, nothing more was done about examining the carbonate-rocks except to have some analyses completed by Dr. M. H. Hey.

In view of the interest now attaching to these carbonate-rocks and because of the discovery in them by Mr. T. Deans of the minerals pyrochlore[2] and monazite, it seemed important to complete the petrographic description of Dr. Dixey's collections of these rocks especially as in the course of the work other interesting rare-earth minerals have been identified.

In preparing these notes I have had the advantage of frequent discussions with Mr. Deans, both before and after his visit to southern Nyasaland in 1951, and I have had access to his 'Preliminary report . . .' and 'Interim report on pyrochlore and monazite in the Chilwa Series of Nyasaland', issued in 1952. I am indebted to the Director of Colonial Geological Surveys and to Mr. Deans for permission to use the maps issued with that report.

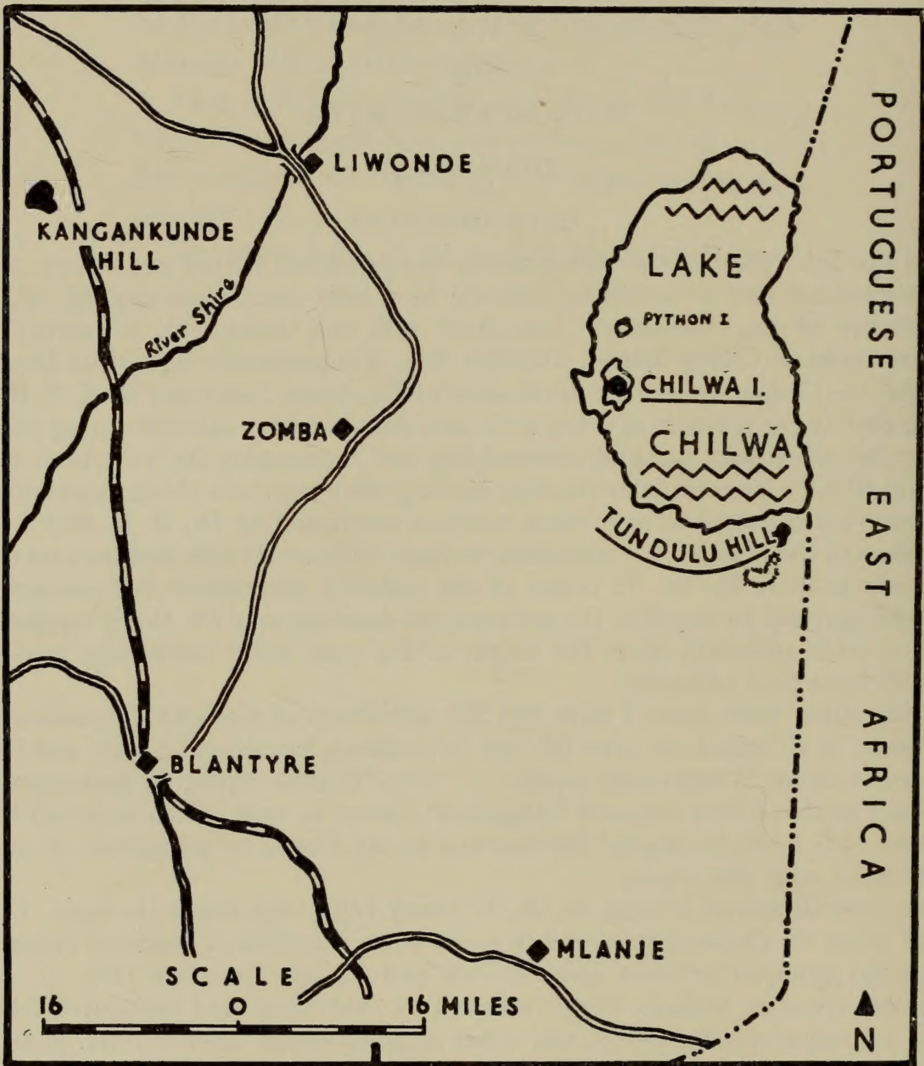
The rocks described in 1934 by Dr. F. Dixey (1935: 23) under the term 'Chilwa Series' occur on Chilwa Island and in many other localities of southern Nyasaland principally grouped between Lake Chilwa and Mlanje Mountain (Fig. 1). They comprise: syenites, volcanic vents occupied by carbonates and brecciated feldspar rocks, nepheline-syenite, ijolite; and dikes of sölvsbergite, microfoyaite, phonolite, and nephelinite.

They are similar in many respects to the rocks of another group of vents 120 miles to the south-west in Portuguese East Africa which can be shown to be intersecting Karroo sediments, dolerites, and Karroo boundary faults, and which are in some places overlain by sediments and lavas of early Cretaceous age. Dr. Dixey believes the vents may be regarded as of late Stormberg (Karroo) age.

[1] References in parentheses are to the list of works on p. 119.

[2] Only a single crystal, then doubtfully identified as koppite, had been noted in a section of one of the Chilwa Island carbonatites in 1937.

The larger vents range in diameter from one nearly 4 miles in diameter (Muambe, in Portuguese East Africa, referred to in the preceding paragraph) to one only ¼ mile across, and there are seven smaller vents whose diameters are no more than a few yards.



PART OF SOUTHERN NYASALAND

FIG. 1

To quote Dr. Dixey (1937: 7):

The vents typically assume the form of composite necks, and they are characterized by the presence of agglomerates or breccias, comprising masses of the intrusive rock, usually the felspathic type, set in a base of similar material, or fragments of the country rocks and of earlier intrusives set in a sparse felspathic, calcareous, or other base. Moreover, in at least five of the

nine larger vents crystalline calcium carbonate, and to a less extent iron and manganese carbonates, are abundantly developed in great masses and are invariably in intimate association with the felspathic intrusive, usually rich in orthoclase and showing agglomeratic forms.

Most of the larger vents have the form of vertical pipe-like intrusions of roughly circular or oval cross-section. One of the most regular and best developed is that of Chilwa Island (Fig. 2), in which the vent occupies a roughly oval area measuring 1½ by 1⅞ miles, and on which the limestone encircled by gneiss is exposed to a depth of 1,400 feet. Tundulu (Fig. 3), lying just south of Lake Chilwa, measures 1 by 1½ miles, has a central cone of carbonatite and agglomerate and an outer, discontinuous ring of carbonatite, feldspar-rock, and agglomerate forming ridges and peaks up to 750 feet in height. Between this outer ring and the central cone is a low-lying floor partly occupied by nepheline-syenite.

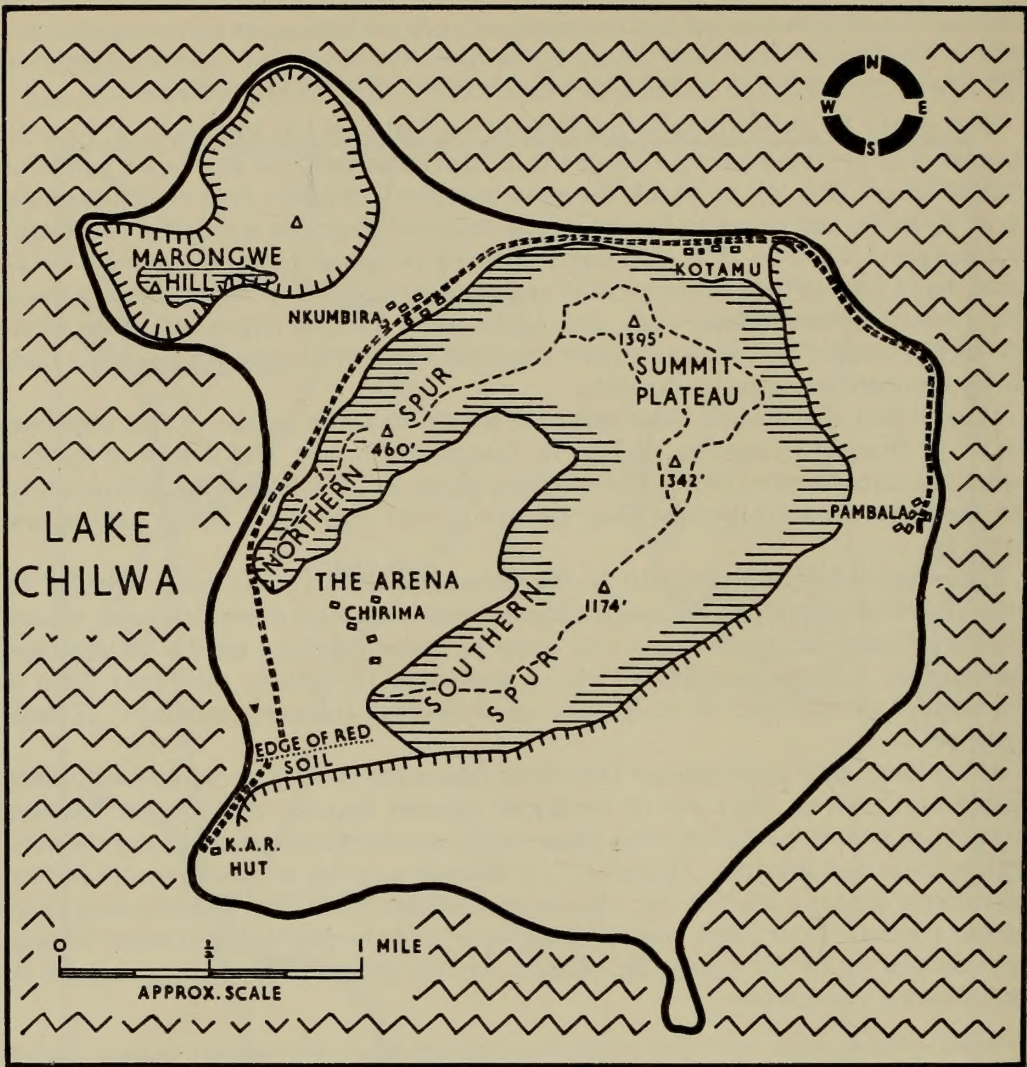
The gneisses surrounding these vents are altered in a way similar to that observed by W. C. Brøgger in the Fen district in Telemark, Norway, and described by him under the term 'fenitization'. The resulting rocks and the feldspathic intrusives of the vents have been fully described by the present author (in Dixey and others, 1937: 43).

The relations of the carbonatite to the feldspathic intrusive are very variable. In some places carbonate and feldspar-rock are 'sharply segregated into irregular masses or parallel bands or streaks, they may occur as vaguely defined bands, the one type may appear as numerous small clots or masses in the other, they may form a thoroughly mixed rock, or they may show normal intrusive relations' (Dixey, 1936: 10).

Altogether, apart from the fact that these carbonatites carry pyrochlore and other interesting minerals, they are of particular interest because they appear in what seems to be intrusive relations with other rocks or as the main constituent of the vent agglomerates and breccias. Moreover, it is difficult to point to a local source for the calcium carbonate, either in the Basement Complex or in any neighbouring sedimentary series. Their origin remains a mystery, and the position as it stood in 1937 was summed up by Dr. Dixey, Mr. Bissett, and the present author (1937: 19, 20) in the following paragraphs:

General considerations show that sedimentary formations are also unlikely to have yielded the limestone. Nothing is known as to former distribution of the Umkondo or Sabi (Waterberg) limestone in this region, but . . . the Karroo of the Lower Shire-Zambezi area rests upon the Basement Complex. But even the Umkondo limestone, which is only a few hundred feet thick, could not have furnished a block of uniform unbedded limestone of the kind described upwards of 1,400 feet thick. The Karroo sediments certainly extended over part of the area considered, but thick limestones are unknown in the Karroo of this region. It may be added that no trace of sediments, such as might be expected to occur with blocks of sedimentary limestone of the size considered, has been observed in association with the limestone of the vents.

In the absence, therefore, of any possibility of explaining the limestones of the vents as relics either of metamorphic limestones of the Basement Complex or of sedimentary formations one is forced to the conclusion that their origin is in some way connected with the magma responsible for the vents and for the orthoclase rocks which occur therein in such intimate association with the limestones. The detailed mineralogical study of the limestones has not yet been completed and will be the subject of a later publication, but up to the present it does not seem possible to explain their composition or distribution in this region as due to carbonate replacement suggested

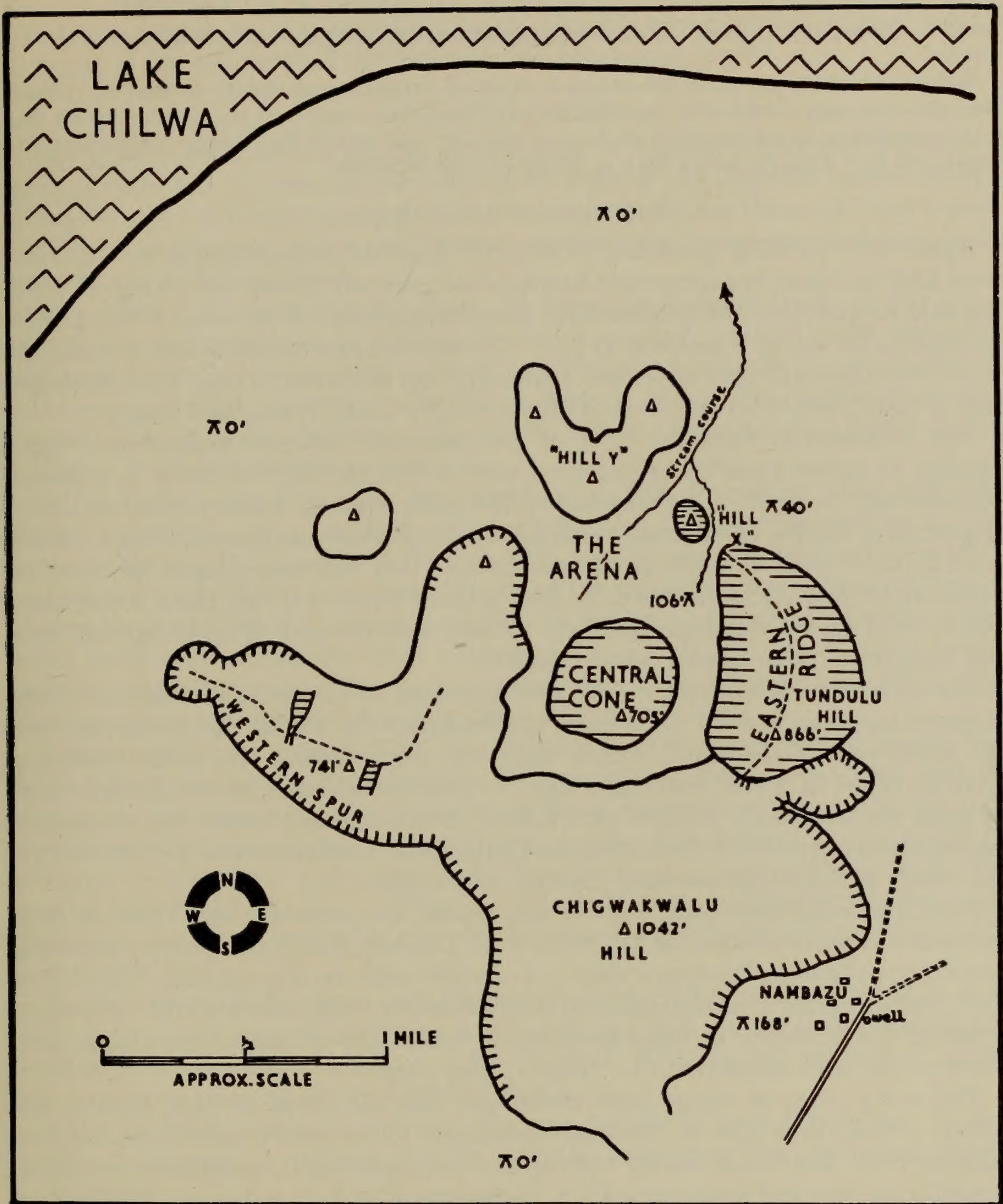


CHILWA ISLAND

Tracing (uncorrected) from aerial photographs

	Carbonatite and agglomerate	Δ	Height (in feet ± 30) of summits above level of lake
	Basement Complex		Crest lines

FIG. 2



TUNDULU & CHIGWAKWALU HILLS

Tracing (uncorrected) from aerial photographs

Carbonatite and agglomerate

Basement Complex

Height (in feet $\pm$ 30) above surrounding plain at three points selected as zero

Crest lines

FIG. 3

by N. L. Bowen (1924) as an alternative explanation of the origin of the limestones of the Fen district.

Without claiming for these limestones a mode of emplacement similar to that of ordinary intrusions one may confidently regard them as of magmatic origin and comparable to the magmatic limestones or carbonatites of Alnö in Sweden, and of the Fen district in Norway, but developed on a scale far larger than at either of these localities.

THE ROCK SPECIMENS

Apart from the early specimens [N167, 168, 169][1] the rocks collected by Dr. Dixey from Chilwa Island are comprised between the numbers N1267 and N1297, of which the field descriptions and localities are listed in Appendix F of Bulletin No. 5 of the Geological Survey of Nyasaland (1937). The carbonatites in this series of specimens came from the north spur of Chilwa Mountain, from Kotamu [N1279], from Marongwe Hill [N1290], and from the crest of Mount Chilwa itself [N1294 and 1295].

The carbonatites from the crest of the mountain are even-grained (0·5 mm.), ranging in colour from cream-coloured with a pinkish tinge in parts to a general pinkish-buff. Some show isolated tawny, limonitic patches, others present a mottled appearance, calcite areas being outlined by the brown patches and veins. Pyrite crystals are visible in some of the specimens. One weathered small block of the carbonatite [N1294] is traversed by finer-grained bands 2–3 cm. thick which stand out in relief on the weathered surfaces. These were thought to be feldspathic rock, but they prove to be almost wholly calcite.

The carbonate-rock intermixed with feldspar-rock at Kotamu resembles the cream-coloured carbonatite from the crest of Chilwa Mountain, but all the specimens from the north spur of the island [N1272–1273] and from the east end of the south spur [N1278] range in colour from light drab to greyish-olive and brownish-drab: some of them are irregularly banded with lighter, cream-coloured bands, but the general impression is of brownish-drab crystalline limestones. Cinnamon-drab better describes the colour of the single specimen from the south spur.

From the other area dealt with in this report, Chigwakwalu and Tundulu Hills, carbonatites were collected by Dr. Dixey from Tundulu Hill [N1176, 1177, 1183–1185, and 1189] and from a limestone 'dike' 3 to 4 yards wide on Chigwakwalu Hill [N1375–1380] and an earlier specimen [N1159] labelled simply 'Chigwakwalu Hill'. Dr. Dixey reported the limestone at these localities as 'essentially similar to the Chilwa limestone in its main characters . . .' (Dixey, 1937: 12).

The rocks range in colour from cream and pale olive-buff to dark brown. The brown carbonate is seen in the hand-specimens to be closely associated with the feldspar-rock, sometimes merely veining and impregnating it, sometimes containing irregular patches and fragments of it.[2] In the pale olive-buff carbonate [N1375] from the 'dike' on Chigwakwalu Hill thin streaks of pink material stand out on the weathered surface. These were taken for feldspar-rock, but they proved on examination to be formed by concentrations of granular apatite in discontinuous bands each

[1] Figures in square brackets refer to specimens. Those collected by Dr. Dixey on the Nyasaland Geological Survey are preceded by the letter N; those collected by Mr. Deans in 1951 by DN, and the figures preceded by B.M. refer to entries in the rock register of the Department of Mineralogy, British Museum (Natural History).

[2] Ibid., p. 8.

2 to 3 mm. thick. In other samples from the dike the apatite occurs in small patches throughout the rock instead of in more or less continuous bands.

MINERALOGY

The chief constituent of all the carbonatites of Chilwa Island and Tundulu is calcite. Chalybite is probably represented by some of the limonitic pseudomorphs, and some of the carbonates may have been manganiferous as there are local concentrations of manganese oxides, and there is an iron and manganese rich core in the central area of Chilwa Island.

The *calcite* is frequently quite clear. In some fine-grained bands [N1294] it is turbid; in some specimens it is clouded with very small, unidentifiable inclusions, and quite commonly it contains regularly disposed minute rhombs of a rhombohedral carbonate of higher refractive index (Pl. 7, Fig. 5). Grains are commonly allotriomorphic, but in some specimens the calcite shows predominantly rhombohedral outlines. Twinning on (110) is common.

In the carbonatite of a 'dike' on Chigwakwalu Hill the calcite forms long lens-shaped crystals up to 3 cm. long. These appear on broken rock surfaces as long cleavage blades. In thin section they are seen to be repeatedly twinned on (110).

Apatite is best developed in bands in one of the specimens from the north spur of Chilwa Mountain [N1273], where it appears in the form of very small ovate grains. Some sections of specimens from Chigwakwalu Hill [N1375, 1377] show sector-twinned crystals recalling the carbonate-apatite (dahllite) described by H. von Eckermann from a calcite-carbonatite from Alnö (1948: 127).

Feldspar whenever present in the carbonatites has the appearance of having been derived from the feldspathic intrusives, and analyses of those have shown that the feldspar is orthoclase remarkably rich in potash (Dixey and others, 1937: 43). It is always turbid, brown-tinted in thin sections, usually allotriomorphic, but sometimes bounded by cleavages, and occasionally it appears as isolated crystals with rectangular boundaries [N1380]. Refractive index γ' is near and slightly below 1·524. Extinction angles measured on cleavage fragments from N1189 gave on (010), $c : \beta = 20°$, $a : \alpha = 9°$.

Quartz is not at all frequent, but it appears in some of the carbonate-rocks in small amount as a late mineral in druses or veinlets and it is occasionally idiomorphic. Crystals isolated from a specimen from Tundulu Hill [N1177] were short prisms imperfectly terminated by the rhombohedral faces.

Pyrite, as bright cubes, is visible to the unaided eye in some specimens. In thin sections it appears as sections of cubic crystals, sometimes fresh but often altered to limonite.

Magnetite is identified as rounded grains rather evenly distributed in certain bands in two specimens [N1272, 1273*b*] and in the micaceous bands in the carbonate-rocks of Tundulu Hill [N1189].

In addition to pseudomorphs after pyrite there are other opaque limonitic pseudomorphs. These represent at least two kinds of minerals:

(*a*) *A rhombohedral carbonate*. These, for the most part quite opaque, appear in most of the carbonate-rocks. In one case, specimen [N1290], the limonitic opaque

material is distributed as veinlets along cleavage planes and as borders to the rhombs. In specimens from the 'dike' on Chigwakwalu Hill the rhombs show relics of clear carbonate with strong zoning [N1377–1380] (Pl. 7, Fig. 2). In the carbonate portion of the rock from the east end of the south spur [N1278] the unaltered carbonate of the rhombs survives. Slightly yellower than the calcite and of high index, the little rhombs have dark limonitic borders. It has not been determined whether this is chalybite or rhodochrosite or an intermediate member. From the prevalence of concentration of manganese oxides on the island it seems likely that they will prove to be an iron-manganese carbonate.

(*b*) A long prismatic mineral forming groups and clusters of small radiating prisms. At present there is no real clue as to what these represent, but in some specimens [e.g. N1279] they suggest by their form the radiating groups of late-formed aegirine found in the feldspathic intrusive.

Possibly the opaque prisms with cross-sections lozenge-shaped with an angle of about 120° that occur freely as separate crystals associated with apatite-rich bands in N1273*a* (Pl. 7, Fig. 6) may be after yet another mineral. It is probable that when fresher rock specimens are accessible the original mineral of these pseudomorphs may be found. As smaller crystals the same mineral is found in N1274.

The rare, accessory minerals that have remained unaltered and identifiable are:

Pyrochlore, first identified and designated 'koppite' in a specimen from Mount Chilwa [N1294] collected by Dr. Dixey; it was recognized by Mr. T. Deans in quantity as very small octahedra in sections of a specimen in the same collection from Chigwakwalu Hill [N1380]. Mr. Deans subsequently obtained a good concentrate of the mineral from a sample of 40 grams of this rock after treatment with hydrochloric acid and separation in bromoform. These octahedra range from 20 to 80 microns in size and are colourless. As already reported by Mr. Deans: 'An assay of a small portion of this rock by Mr. L. C. Chadwick showed 0·39 per cent. $(Cb,Ta)_2O_5$ equivalent presumably to about 0·6 per cent. pyrochlore. A radiometric assay of a pyrochlore concentrate (25 milligrams in weight) gave 0·13 per cent. equivalent U_3O_8.' Mr. Deans finds pyrochlore in several samples from Chilwa and Tundulu, and has observed crystals up to over 1 mm. across. As seen in thin section of a carbonate-rock from Chigwakwalu they are very small, 0·04 mm., but in sections of other carbonate-rocks [N1278, N1294] from Mount Chilwa they range up to 0·5 mm. across. These are yellowish to brown in colour, and cross-sections show that cubo-octahedral habits are common as well as octahedra (Pl. 7, Fig. 1).

A partial analysis has been made in the Mineral Resources Division of Colonial Geological Surveys on a 0·4-gram sample of dark brown pyrochlore separated by Mr. Deans from a soil sample on the summit of Chilwa Mountain. The results communicated in a report dated 1 September 1952, republished here by permission of the Director of Colonial Geological Surveys, are: $(Cb,Ta)_2O_5$ 64·9, Fe_2O_3 1·4, TiO_2 1·8, ZrO_2 nil, rare-earths and ThO_2 2·6, CaO 16·6. Mr. Deans reports that 'the indications are that the niobium /tantalum ratio (Cb:Ta) is extremely high . . .'.

Minerals of the pyrochlore-microlite series from other areas of carbonatites have been described from Sukulu in Uganda, Alnö Island, the Fen district of Norway, and Kaiserstuhl in Baden, Germany. The Sukulu pyrochlore has about the same iron

content as that from Chilwa, but the 'microlite' from Söve, Fen district,[1] and the 'koppite' from Schelingen, Kaiserstuhl, are both much richer in iron, 8·25 and 9·73 per cent., and Rødland's analysis of the 'microlite' from Söve shows 62·77 per cent. combined columbium and tantalum oxides. The rare-earth content of the Kaiserstuhl 'koppite' is much higher than in the others. J. Jakob (Brandenberger, 1931: 324) found in the koppite from Schelingen Ce_2O_3 8·15, La_2O_3 1·68, Cb_2O_5 56·43, and Ta_2O_5 0·15. An earlier analysis by G. H. Bailey (1886: 153) gave for koppite from the same occurrence cerium earths 6·89, ZrO_2 3·39, and undifferentiated $(Cb,Ta)_2O_5$ 61·64. At present a modern analysis of the pyrochlore from Alnö Island is not available.

Rutile occurs as small crystals and irregular grains, dark brown, translucent in thin section, but black when seen as crystals in the concentrates. The identification of rutile was confirmed on a selected crystal by an X-ray photograph by Dr. F. A. Bannister,[2] who also confirmed the identification of pyrochlore.

Anatase appears in concentrates along with pyrochlore as small square tablets of greenish or pale blue colour. In thin section it is rarely seen. The high refractive indices cause it to appear only feebly translucent and the pale blue colour is not often visible in transmitted light. Anatase was frequent in the concentrate of heavy minerals along with pyrochlore in a specimen from Tundulu Hill [N1189], particularly in some grey and brown micaceous bands.

Zircon has been observed in a few specimens [N1377]. It seems to be associated with the feldspathic rocks and inclusions of these [N1380].

Synchysite 2 [$CaCe(CO_3)_2F$] has been identified by X-ray photographs in specimens of the carbonatites from Tundulu Hill and in a fluorite-carbonate assemblage from the same locality. It has been doubtfully identified at Chilwa Island in thin sections of specimens of Dr. Dixey's collecting as very small crystals included in quartz [N1290, 1294], and it is possible that some small groups of what appear to be prisms, now altered and opaque [e.g. in N1273, N1274], may in fact be groups of thin plates of synchysite.

Lath-shaped sections of a mineral of high refractive index and high birefringence, comparable with that of calcite, were noticed in a specimen from Tundulu Hill [N1176] in 1936, but remained then unidentified. The crystals were wholly enclosed in calcite near the margin of one of a number of feldspar-rock inclusions. In later sections the mineral was found predominantly in drusy patches, where they were evidently of late crystallization (Pl. 7, Fig. 4).

Solution of lightly crushed pieces of the rock in dilute hydrochloric acid left among the undissolved minerals a few small colourless hexagonal plates along with some very small prisms of apatite. The hexagonal plates are uniaxial, positive, and were successfully identified with the birefringent lath-shaped sections of negative elongation. ω was found to be $1{\cdot}6445 \pm 0{\cdot}002$. This did not suffice to identify the mineral and the identification is due to Dr. F. A. Bannister, who successfully mounted a very small crystal on the X-ray goniometer.

The hexagonal crystal first picked for X-ray identification measures 0·28 mm. edge

[1] E. Saether (1948: 67) refers to 'koppite ($CaNbO_3(OH)$)' in the Fen district, and not to microlite, in his preliminary account of the results of his work in the district.

[2] This rutile contains some iron. Sp. gr. 4·35 determined by T. Deans.

by 0·06 mm. thick. Single crystal rotation photographs about the usual axes [10$\bar{1}$0] and [0001] showed its close resemblance to a member of the parisite family.[1]

The synchysite in a dark brown fluorite-bearing carbonate rock from Tundulu Hill [N1177] occurs in small patches of very small crystals, which appear as fibres or exceedingly thin plates in the hand-specimen and as faintly brown turbid patches in thin section. This, too, was identified by Dr. Bannister by means of powder photographs (X5664, 5678).

The little patches of opaque white material afford very poor material for R.I. determinations. The lowest value for the refractive index observed in sodium light was 1·6235.

Baryte was identified in a veinlet and in the calcite of one specimen [N1294] from Mount Chilwa and in one from a limestone 'dike' at Chigwakwalu Hill.

Mica occurs as very small flakes in one carbonate-rock from Mount Chilwa [N1273*b*] and is also an important constituent of a peculiar rock [N1297], a calcite-biotite rock with many pseudomorphs of uncertain origin, from the summit. It occurs also in N1181, a mixed silicate-carbonate rock from Tundulu Hill.[2] It is also abundant in some 'dirty' brown and grey bands in the carbonate rock [N1189] from Tundulu Hill. In this rock it is a biotite. It is very dark green in the hand-specimen and occurs as short six-sided hexagonal prisms and flakes. In thin section it is deep brown (tawny-olive to sepia)[3] by transmitted light and nearly uniaxial. Refractive index (γ') is $1{\cdot}64 \pm 0{\cdot}01$. The associated minerals in these micaceous bands are magnetite, apatite, pyrochlore, and anatase.

The mica in the carbonatite from Chilwa Island [N1273*b*] is biaxial with 2E about 30°. It is pale brown with pleochroism as seen in thin sections: α pinkish-buff, β deep olive-buff, γ fawn colour; and absorption $\alpha < \beta < \gamma$. The refractive indices were not measured as the flakes are extremely small. The mica in N1297 has γ' just below 1·620 and 2E about 25°. Pleochroism in thin section γ' yellow ochre, α' colourless.

Fluorite occurs massive associated with calcite and opaque rhombohedral carbonate of iron (and possibly manganese) in a specimen [N1177*a*] from Tundulu Hill. In thin section it is for the most part colourless, but some crystals show deeply coloured cores of livid purple. The rock itself is dusky brown. On Chilwa Island Mr. Deans has found fluorite abundant in occasional boulders at Marongwe Hill and in The Arena. The colour is dark purple.

Florencite. A pink mineral occurring in DN8*a,b* from Tundulu Hill is doubtfully referred to florencite, a cerium-aluminium-phosphate, only (at present) on its resemblance to a pink mineral isolated in residues insoluble in HCl from certain soil samples. The spectrograph of this mineral indicates much aluminium with cerium, iron, phosphorus, and silicon,[4] and the X-ray photograph agrees with that of a specimen labelled florencite in the British Museum collection.[5]

[1] X-ray film nos. 5641, 5643, 2398, 2399, 2400, 5475, 5688; and powder photographs 5670, 5676.

[2] Other mixed silicate-carbonate rocks, not described in full detail, contain a variety of other minerals—nepheline, aegirine, melanite, and wollastonite—as well as feldspar and calcite.

[3] Colour names used refer to Ridgway (R.): *Color standards and color nomenclature.* Washington, 1912.

[4] Refractive index determined by Mr. Deans is 1·663.

[5] Florencite has also been identified as white patches (X5747) in brown phosphatic material from

PETROLOGY: CHILWA ISLAND

With the minerals and macroscopic appearance of the carbonate-rocks thus briefly described one may attempt short descriptions of the microscopic characters of the specimens, beginning with those from the crest of Chilwa Mountain.

N1294c [B.M. 1935,1211(13*c*)]. A loose boulder showing fine-grained bands of carbonate traversing coarser carbonate. Grain-size of the finer bands averages 0·12 mm. The calcite is turbid; much of it occurs as finer granules between the larger grains. Pyrite and pyrochlore and anatase (?) are present. In the coarser bands grain-size averages 0·6 mm. Near the contact of fine and coarse are some opaque pseudomorphs after (?) pyrite, and patches of fine-grained granular apatite, and a few small patches of allotriomorphic quartz. Some minute, colourless, rod-like inclusions in the quartz may be synchysite.

N1294a [B.M. 1935,1211(13*a*)]. Like the coarser parts of N1294*c*. It is in contact with a deeply altered nephelinite.

N1294b [B.M. 1935,1211(13*b*)]. The specimen in which pyrochlore was first observed.

In this rock the general appearance in thin section is of good crystal plates of calcite with finer material, as it were brecciated, between. This texture is likely to be due to recrystallization. The grain-size of most of the carbonate is about 0·3 mm. The general colour is pinkish-buff. The specimen shows a finer-grained band, grey when fresh, and weathering rough and brown on the surface. This contains much fine-grained calcite and in thin section is seen to be partly feldspathic rock and partly intensely calcitized. The fine-grained calcite encloses many small rounded patches of turbid feldspar, like that in the feldspathic intrusives, associated with colourless quartz (or apatite). These rounded patches are often bounded by a broken ring of small pyrite crystals. It is possible that we have here a clue to the origin of the fine-grained calcite bands. They may be the result of complete calcitization of an original band of the feldspathic rock. A less advanced stage of invasion and replacement of feldspathic rock by carbonate is probably seen in a specimen from the scree north-east of The Arena, Chilwa Island [DN35].

N1295 [B.M. 1935,1211(14)]. The calcite in crystals 0·5 mm. across is very full of dust-like inclusions and contains included rhombs of carbonate of higher index. It is very noticeable that opaque limonitic material is in patches and veinlets pushed aside, as it were, by the calcite plates. The opaque pseudomorphs are after a rhombohedral carbonate. Pyrite, much of it unaltered, is abundant as cubes. A single crystal of pyrochlore was found in one section.

This concludes the record of Dr. Dixey's rocks from the crest of Mount Chilwa except for one specimen [N1297], a peculiar type with abundant biotite both as insets and in groundmass with calcite. There are abundant pseudomorphs with shapes suggesting olivine now consisting of calcite-limonite(?)-mica.

The specimen N1279 [B.M. 1935,1211(10)] from Kotamu shows a white medium-grained calcite-rock, in which lie some dark brown patches and specks and irregular

Python Island [N1285, 1287] which contains white veins (X5721) and rare greenish lenticles (X5708) of which the powder photographs suggest redondite, a hydrated phosphate of aluminium and iron.

areas of pink feldspar, veining the pink feldspathic intrusive. The appearance of the rock in the field is well described by Dr. Dixey (1937: 11), and the hand-specimen is figured (ibid., Pl. III, Figs. 5 and 6). The carbonate-rock is similar to the last described from the crest of Mount Chilwa. Individual idiomorphic feldspars lie free in the calcite. Opaque pseudomorphs of a rhombohedral carbonate are frequent. Pyrochlore crystals are observed in thin section. Examination of thin sections across the junction of the carbonate-rock and feldspathic intrusive gives one the impression that the carbonate is a wholesale replacement of the feldspathic rock, which has left relics of feldspar unabsorbed. Apatite grains and small interstitial areas of late quartz are present.

A specimen N1278 [B.M. 1935,1211(9)] from the east end of the south spur of Chilwa Island shows similar relations between carbonate and feldspathic intrusive as do the specimens from Kotamu. The carbonate is light drab in colour and the calcite well crystallized, grain-size averaging 1 mm. Between the calcite plates small opaque rhombs of a rhombohedral carbonate are concentrated. Some of the original carbonate remains. This rock shows more pyrochlore in thin sections than any other examined. Apatite occurs sporadically as rounded grains and there are many small groups of opaque, radiating prisms. In a veinlet containing quartz and calcite similar opaque prisms fringe minute crystals that are probably apatite. Rutile is a rare accessory. Opaque pseudomorphs with square sections (up to 0·75 mm.) are probably after pyrite (Pl. 7, Fig. 1).

The limestone of the north spur, Chilwa Island, is represented by specimens [N1272, N1273, N1274*a*] from blocks in the feldspathic intrusive. These present several variations:

N1272 [B.M. 1935,1211(4)]. A well-crystallized carbonate-rock, light drab in general colour, with calcite showing rhombohedral outlines on numerous cleavage surfaces. Individual crystals range up to 5 mm. across. The intercrystal areas are occupied by thin veinlets and patches ranging in colour from russet to pink. In thin section these are seen to consist of apatite, very fine-grained almost cryptocrystalline, with feldspar, calcite, and opaque minerals some of which are limonitic pseudomorphs of one or more different minerals of various forms: radiating groups of small prisms, cubes, and a few rhomb-shaped sections. The colour of the pseudomorphs in thin section by reflected light is reddish-brown to dark brown. One or two crystals of pyrochlore were seen in thin section.

A specimen of similar composition is a mottled dark brown and drab, highly crystalline carbonate rock collected by Mr. Deans in October 1951 from the foot of Chilwa Mountain, south-east of Kotamu [DN27]. The thin section showed two rather shattered crystals of pyrochlore about 0·25 mm. across.

N1273 [B.M. 1935,1211(5)] is represented by two specimens of even-grained (1–2 mm.), banded limestone ranging in colours from cream to drab, brownish-drab, and dark greyish-olive. The darker bands in one specimen carry abundant limonitic pseudomorphs of a mineral of acicular prismatic habit distributed in groups and individuals in fine-grained granular apatite and calcite (Pl. 7, Fig. 6). The apatite is in minute ovate grains and is the main colourless constituent of these bands. Most of the pseudomorphs seem to be after a prismatic mineral giving long thin longi-

tudinal or lozenge-shaped oblique cross-sections, but some rhomb-shaped sections are seen and it is quite likely two minerals are represented.

In a dark greyish-olive band there are small magnetites as well as a few limonitic pseudomorphs fairly evenly distributed in equigranular calcite, showing twinning. Pyrite occurs and is partly altered to limonite. Apatite is very rare, but occurs as grains similar in size to the magnetite. The texture of the rock in this band is granulitic. A little pale biotite occurs as isolated flakes and small interstitial patches.

A darker coloured carbonate-rock from one of these blocks in the feldspathic intrusive [N1274*a*] [B.M. 1935,1211(6)] carries some unaltered magnetite. In other ways it combines most of the characters of the specimens just described. Some short prismatic, opaque pseudomorphs are free in apatite-patches, but much of the opaque material is massed in patches round the magnetite. Late veins penetrating the carbonate-rock are filled with opaque material. Black ridges weather out on the surface and should be tested for manganese oxides. The colour of the rock is dark livid brown and the calcite averages about 0·5 mm. in grain-size.[1]

The carbonatite of Marongwe Hill, where a small vent breaks through the gneiss (Dixey, 1937: 11), is represented by N1290, a speckled brown and white limestone, grain-size 1·7 mm., in which opaque limonitic pseudomorphs are evenly distributed. There are a few cubes, probably pyrite. Apatite occurs rarely as small patches of very small grain-size. There are some small areas of clear quartz. In places the quartz carries some very small inclusions that may be pyrochlore, and minute lath-shaped sections that are probably synchysite. The calcite shows curved lines of undulose extinction in polarized light.

PETROLOGY: TUNDULU HILL

N1176 [B.M. 1933,355(48) and (48*a*)]. Crystalline granular calcite-rock, 1 to 2 mm. grain-size; vinaceous fawn in colour, containing large patches and streaks of pink feldspar-rock. The calcite is accompanied by abundant opaque pseudomorphs, many of them with the form of rhombs, probably after chalybite. Small plates of synchysite are seen both enclosed in calcite and in druses. Solution in dilute hydrochloric acid liberates much limonitic material (rhombs, cubes, and 'amorphous'); small white prisms of apatite; colourless, very small, hexagonal plates of synchysite; and some square plates (0·045 mm.) of anatase. Pyrochlore, not seen in thin section, is rare in the insoluble residue.

N1177a–c [B.M. 1934,131(16–18)]. These, not themselves carbonate-rocks, may be closely associated with them and with the feldspathic intrusive.

(*a*) A dark brown compact fluorite-chalybite-quartz assemblage contains small white patches of extremely small plates of synchysite. The chalybite is altered and quite opaque.

[1] Other blocks in the feldspathic intrusive from the northern spur of Chilwa [N1274*b* and *c*] are dark olive-grey medium-grained rocks. They are mixed calcite-silicate rocks presenting various assemblages in different bands or patches of aegirine-calcite and melanite-calcite-aegirine-apatite with varying amounts of magnetite. A somewhat similar rock is N1271, also from the northern spur of Chilwa Island, in which various bands present calcite-aegirine-magnetite-apatite with little biotite, and melanite-nepheline-aegirine-calcite with little apatite. Related types from Tundulu mentioned below are N1181, N1195, and DN7.

(*b*) A magnetite-zircon-orthoclase assemblage. A much-weathered specimen. Grain-size 1 to 2 mm.

(*c*) A fine-grained apatite-magnetite assemblage with some feldspar. Apparently a band, perhaps from a carbonate-rock.

N1181 and N1195, like N1271 and N1274 from Chilwa Island mentioned just above, are mixed calcite-silicate rocks. They are compact deep to dark olive-grey rocks with granulitic texture. N1181 is mainly a calcite-feldspar-biotite-magnetite assemblage. DN7, collected by Mr. Deans on the crest of the eastern ridge near the north end, is a calcite-magnetite rock with small amounts of apatite, biotite, wollastonite, and cubo-octahedra of pyrochlore. Large octahedra of magnetite weather out on the surface. N1195 is more complex than either of these and more nearly resembles the two Chilwa calcite-silicate rocks. In various parts it presents the following assemblages: calcite-feldspar-apatite, calcite-nepheline-aegirine-feldspar, calcite-melanite-feldspar, and calcite-melanite-nepheline.

Another rock of this type is from the eastern dike at the western end of Chigwakwalu Hill [DN13*a*]. It is an aegirine-calcite assemblage with abundant apatite, some biotite, and a trace of magnetite. The aegirine is in stout prisms.

N1183–5 [B.M. 1933,355(44–46)]. The carbonate parts of these specimens, which are mixed carbonate and feldspar-rocks, are dark brown veins and patches permeating and cementing the brecciated feldspar-rock. Thin sections show the carbonate to consist largely of calcite with rhombs of opaque, altered chalybite now replaced by brown limonite. Accessory minerals are apatite and occasional free quartz in druses. In some of the druses there are small prisms of synchysite. N1185 has been analysed (see p. 115).

The white carbonatites of Tundulu Hill [N1189*a* to *c*] range from an apparently pure, rather coarsely crystalline, light-buff coloured limestone with occasional brown bands and patches to a finer-grained type with colour cream to cinnamon-drab and grain-size averaging about 1 mm. with browner bands weathering out in relief.

N1189a [B.M. 1934,131(5)]. The calcite contains many inclusions of transparent colourless rhombs of higher refractive index regularly arranged. Opaque pseudomorphs usually with the forms of cubes or rhombs tend to concentrate along intergranular boundaries of the calcite. Other accessory minerals observed are apatite, pyrite, and synchysite, the last forming sheaves of thin plates in drusy cavities. The darker bands are rich in biotite as small flakes and stout hexagonal plates (deep brown in thin section, nearly uniaxial, and with refractive index near 1·64) associated with magnetite, orthoclase, apatite, some pyrite, and much pyrochlore as very small cubo-octahedra.

N1189b [B.M. 1934,131(6)]. Similar to the above. It contains bands and patches of altered chalybite and occasional small bunches of plates of synchysite. Pyrite as small cubes is visible in the hand-specimen.

N1189c [B.M. 1934,131(7)]. A specimen collected to show differential weathering. Feldspar-rock with a broad band of even-grained (1–2 mm.) 'limestone' with many brownish streaks.

N1159 [B.M. 1933,355(35)]. An early specimen from Chigwakwalu Hill is a fine-grained calcite-rock containing as accessory minerals scattered rounded grains of

apatite, small cubes of pyrite, and some included fragments of feldspar and quartz. In its grain-size and general characters it resembles the fine-grained bands of calcite in the banded specimen from Mount Chilwa [N1294]. The carbonate in this specimen is impregnating a feldspathic breccia in which are relics of fenitized country rock.

N1375 to N1377 [B.M. 1935,1211(110–112)]. These consist mainly of calcite, grain-size 0·6–1·0 mm., associated with granular apatite, sometimes concentrated in bands, opaque rhombs of limonitic material, presumably pseudomorphs of chalybite, a few relics of turbid feldspar and rather rare, minute flakes of synchysite, often in drusy patches. Also in druses are small areas of clear, rounded crystals of quartz. The calcite itself is crowded with very small inclusions. Some sections [N1377] showed small grains doubtfully referred to zircon. A small sector-twinned crystal of apatite was observed in sections of the same rock. No pyrochlore was seen in sections of these specimens.

A bulk analysis of one of these specimens, N1377, even-grained and relatively free from macroscopic patches of apatite or feldspar, was made by Dr. M. H. Hey and is discussed below (p. 115).

N1378–1380 [B.M. 1935,1211(113–116)] from the 'dike' on Chigwakwalu Hill. These are all dark carbonatites ranging in colour from drab to olive-brown. Two of these [N1378,1380] show an unusual type of calcite crystallization well seen on weathered surfaces. The calcite forms long, flat, lens-shaped crystals up to 3 cm. long, forming groups of divergent crystals between which lie concentrations of small (1 mm.) black rhombs of altered chalybite. In thin section these calcites appear as long blades crossed by closely spaced twin lamellae. Some of the calcite contains little, regularly arranged, rhombs of dolomite or chalybite. One section showed abundant *pyrochlore* in very small crystals (0·04 mm.), and the same section shows many small crystals and groups of synchysite, and also small grains of quartz in druses. Other minerals observed, though rarely (in N1380), are apatite, baryte, and associated probably with the feldspar-rock, crystals of zircon. The distribution of pyrochlore must be very uneven, for some sections show none at all and in others the tiny crystals are abundant. Mr. T. Deans first observed pyrochlore in sections of this rock and subsequently obtained a good concentrate from a 40-gram sample after treatment with hydrochloric acid.

N1379 [B.M. 1935,1211(114)]. A compact, black and tawny specimen from the 'dike' consists mainly of chalybite and its limonitic pseudomorphs. Rare patches containing plates of synchysite and occasional small groups of granular quartz are seen in the section.

A similar specimen was collected by Mr. Deans in 1951 from the eastern side of the eastern ridge of Tundulu [DN4]. It is a heavy, dark brown rock with some black patches, probably manganese oxides, and some dull white patches with occasional pink grains that may be florencite.

Another specimen [DN21*b*] from the western 'dike' on the western spur of Chigwakwalu Hill shows in the hand-specimen a remarkable concentration of pale blue anatase in a fine-grained aggregate of quartz and apatite with scattered rhombohedral pseudomorphs after carbonate. No pyrochlore was identified in this specimen

in the thin section and only one small druse containing small crystals of synchysite was observed.

Specimens [DN8*a–d*] collected by Mr. T. Deans in 1951 from the western foot of the central cone of Tundulu appear to be rich in pyrochlore and in synchysite. These rocks are dark brown (sepia to tawny olive) in general colour on weathered surfaces but with extensive patches coloured pinkish-buff. On broken surfaces the rocks show large areas vinaceous pink to pinkish-buff with many small (0·5 cm.) patches and streaks of dark olive and fewer patches of dead white, chalky looking material. One specimen [DN8*a*] shows thin, roughly parallel layers of dark brown splotched with orange (ochraceous orange) and white layers with small patches of pink. These layers are all irregular and not continuous. The hand-specimens are described in some detail because these rocks seem to be relatively rich in the rare minerals pyrochlore and synchysite.

A suite of specimens from the southern foot of the central cone [DN16*a–c*] are similar in general appearance to the above except that the prevailing dark brown colour of the darker bands is replaced by a yellow ochre which seems to be due to a further alteration of the iron carbonates. They seem to carry less visible pyrochlore and more synchysite than the specimens [DN8] from the western foot of the cone.

The mineralogy of these rocks is very complicated and requires considerably more research than it has been possible to devote to it at the present time. As far as at present appears, the dark areas consist partly of opaque dark brown 'amorphous' material often with a concretionary or mammillary form in the central parts but usually showing pseudomorphs of rhombohedral crystals on the outer parts of the bands and patches. These consist of transparent carbonate (calcite) crowded with opaque brown inclusions, iron oxides and perhaps manganese oxides, lying, in general, along the cleavages. The yellow ochre colouring in the dark bands is presumably due to hydrated iron oxides (limonite).

The lighter bands in DN8*a* are partly granular apatite (0·05 mm.) impregnated with calcite, and partly patches and bands of clear calcite in which are some half-millimetre crystals of pyrochlore, blades of synchysite, and idiomorphic apatite. The appearance is as if the carbonate, carrying the constituents of pyrochlore and synchysite, had invaded and broken up the dark carbonate bands. Some quartz comes in with the calcite, and there are areas where the calcite is mottled and partly replaced by a mineral believed to be florencite which is visible as pink patches in the hand-specimen.

In another example [DN8*b*] the white and pale pink areas consist of granular quartz with abundant apatite, small crystals of pyrochlore (0·06 mm.), and turbid, nearly isotropic material that again may be florencite. Pyrochlore, the turbid colourless mineral and free pseudomorphs of 'chalybite' and small, highly refracting and birefringent crystals identified as anatase are abundant in the neighbourhood of the dark brown areas. Parts of the quartz-apatite regions are impregnated with calcite, and there are 'pools' of clear calcite and quartz nearly all containing blades of synchysite and free idiomorphic apatites (0·06 mm.).

In DN8*c* some of the calcite plates and some small areas of quartz are crowded with very small hexagonal prisms with negative elongation. These are almost cer-

tainly apatite. Where they lie in quartz it can be seen that they have high refractive index and low birefringence. Where they lie in plates of calcite their refractive index is evidently intermediate between the two refractive indices of calcite and it can be shown to be not very much lower than the refractive index for the ordinary ray, 1·658. Thus in a plate of calcite nearly normal to the optic axis the included crystals are almost invisible, whereas in calcite plates showing high birefringence the included prisms stand out in strong relief, particularly in one position of extinction of the calcite. In these highly birefringent calcite plates the appearance of the little prisms between crossed nicols suggests that they are themselves highly birefringent, but if, as I believe, they are the same as the prisms in the neighbouring quartz plates, this effect must be due to their extreme thinness, so that what one sees is the almost unaltered retardation of the calcite that lies above or below them. In cross-section they measure up to 0·007 mm. The thickness of the section is about 0·02 mm.

Some plates of the calcite carry many inclusions of synchysite as well as apatite. Larger blades of synchysite are very common, and pyrochlore, as crystals up to 0·6 mm. across, fairly so. The main part of the section is occupied by the dark areas of altered iron (and manganese) carbonates.

In DN8*d* the calcite plates are mottled in a curious manner. Between crossed nicols the plates are broken up into islands of high birefringence in areas of slightly lower interference tints. The plates extinguish uniformly as a whole. In polarized light that has traversed the polarizer with the vibration direction parallel to the 'fast' vibration direction in the calcite there is little difference in relief observable between the 'islands' and the 'sea': the two minerals, if two minerals they be, have their lower refractive indices not greatly different. In the position at right angles to this with vibration direction corresponding to the 'slow' ray (ω') the relief is very noticeable. In this position it is seen that the mineral with the higher birefringence has also a slightly higher refractive index than the ordinary index for calcite. It is as if within the calcite there was taking place exsolution of another mineral, perhaps a carbonate, with a lower refractive index not far from ϵ for calcite and a higher index greater than ω, namely 1·658. Any of the rhombohedral carbonates from dolomite to ankerite could meet these conditions. If the calcite could be isolated chemical or spectrographic analysis would give a clue to the explanation of this mottling effect. It is tempting, considering the rocks with which one is dealing, to look for rare earths as an underlying cause, and some of the plates of calcite in the same section do show minute blades of synchysite. However, these have no definite orientation and the 'islands' of higher birefringence are still to be seen.

For the rest the rock is closely similar to DN8*c* described above. The rhombohedral pseudomorphs are very well developed and synchysite is abundant, but pyrochlore was not seen in thin sections.

In the specimens from the southern foot of the central cone [DN16*a*–*c*] synchysite is abundant in the colourless calcite patches and apatite is often present also. In the dark patches, parts are altered to translucent brown limonite, as I suppose it to be. The apatites are about 0·2 mm. across and the synchysite blades occasionally measure 1 mm. in length. Pyrochlore was only seen in one section of these rocks and then as very small crystals (0·03 to 0·06 mm.). The pink mineral in these rocks is less

conspicuous than in the specimens from the western foot. It seems to be represented in thin sections by turbid patches of birefringent material, usually round the synchysite: it may also occupy veins in the opaque dark areas.

CHEMICAL ANALYSES OF THE CARBONATES

Three of the carbonate-rocks have been analysed in the Department of Mineralogy by Dr. M. H. Hey and one of the same rocks was also analysed by Mr. S. E. Ellis.

One of the analysed rocks [N1377, B.M. 1935,1211(112)] is from the limestone 'dike' on Chigwakwalu Hill and is a cream to pale buff 'limestone' apparently free from feldspathic material. The other two are brown carbonate-rocks, one veined by feldspar-rock [N1380] from the same 'dike' on Chigwakwalu Hill; the other [N1185] forming merely matrix in a feldspathic breccia.

For each of the first two rocks [N1377, N1380] bulk analyses of the whole rock were made, and careful determinations were also made of the percentage of some of the oxides dissolved by treatment with 2N hydrochloric acid over a water-bath for from 3 to 4 hours.

The results for these two rocks are set out in Table I. The oxides have been listed in the order used by H. von Eckermann in his Alnö memoir (1948).

In N1380 the feldspathic veins were few and clearly marked with sharp contacts against carbonate. Care was taken to choose for analysis carbonate as free as possible from visible feldspathic material, and the result shows that this was done quite successfully.

Considering first the analysis of N1377, calculations indicate that Cb_2O_5 0·04 per cent. represents about 0·06 per cent. pyrochlore, the rare-earth oxides 0·05 per cent. are almost certainly present as synchysite 0·075 per cent., and the rather high percentage of P_2O_5 3·18 represents about 7·5 per cent. apatite.

The SrO is high at 0·23 and, with nearly all the BaO, is found again in the soluble portion. Assuming the SrO to be present as strontianite, it requires 0·1 per cent. CO_2. The remaining CO_2 is insufficient to combine with all the remaining CaO, about 0·7 per cent. CaO remaining unallotted, and there is no CO_2 available for MgO or MnO not accountable as free oxides.[1] The small content of alkalis is allotted to feldspar (0·9 per cent.), and there remain sufficient Al_2O_3 and SiO_2 to form with 0·1 per cent. CaO a small amount of anorthite 0·53 per cent. No plagioclase was observed in the sections, and it may be noted that nearly all the Al_2O_3 0·35 per cent. was found in the soluble portion of the rock.If no SiO_2 were allotted for feldspar the total SiO_2 0·88 could be considered as wollastonite and magnesium metasilicate. No wollastonite or pyroxene, however, was observed in the sections. On the other hand, a mineral occurring in cavities in the limestone is uniaxial (+) and with refractive index slightly higher than balsam and has been referred to quartz. There seems to be insufficient free SiO_2 for this however one distributes the available CaO, MgO, and alkalis.

In N1380 the analysis presents a similar problem. CaO, MgO, and available MnO are again in excess of the CO_2, but in this case there is sufficient SiO_2 left for free quartz even if SiO_2 is allotted to CaO for anorthite, pyroxene, and wollastonite.

[1] Dr. Hey has suggested that MgO may be present as brucite (but brucite has not been identified) and that most of the BaO and MnO are present as psilomelane.

TABLE I

	1	1a	2	2a	3	4	4a
SiO_2	0·88	..	4·29	..	3·36	41·89	0·31
CO_2	38·38	n.d.	34·88	n.d.	32·80	11·03	n.d.
TiO_2	0·18	0·07	0·23	n.d.	0·30	0·91	0·02
Al_2O_3	0·37	0·35	1·32	0·21	1·69	8·69	1·87, 0·39*
Fe_2O_3	2·62	1·90	9·28	4·43	6·13	9·82	1·73, 3·50*
FeO	nil	..	nil	..	2·99	nil	..
MnO	0·39	0·35	0·96	n.d.	0·31	1·00	0·41
MgO	0·31	..	0·25	..	3·10	0·22	0·07
CaO	53·60	n.d.	45·62	n.d.	44·35	13·36	13·12
Na_2O	0·09	..	0·06	..	0·04	0·31	..
K_2O	0·03	..	0·22	..	0·50	7·59	..
P_2O_5	3·18	..	0·03	..	3·26	0·08	..
F	0·06	n.d.	nil	..	c. 0·28	0·04	..
H_2O+	nil	..	1·20	..	0·16	1·85	..
H_2O-	0·06	..	0·35	..	0·14	0·40	..
ZrO_2	tr	..	tr	..	..	0·04	..
Cb_2O_5	0·04	nil	0·30	nil	0·80	0·25	nil
Ta_2O_3	tr	nil	tr	nil	..	tr	nil
SO_3	n.d.	n.d.	0·22	..	0·06	0·22	0·02
S	—	..	..	..	0·42	nil	..
Cl	tr	..	0·01	..	0·02	0·02	..
$(Ce, Y)_2O_3$	0·05	n.d.	0·40	0·40	n.d.	0·20	0·20
Cr_2O_3	n.d.	..	n.d.	..	..	n.d.	..
BaO	0·08	0·06	0·40	0·18	0·10	0·20	0·07
SrO	0·23†	0·23†	0·11	0·10	n.d.	0·06	0·04
available O	0·013	..	0·07	..	..	0·13	..
Total	100·46	..	100·20	..	100·81	99·68	..

1. Carbonatite from the 'dike' on Chigwakwalu Hill, Tundulu, Southern Nyasaland. M. H. Hey anal. [N1377, B.M. 1935, 1211 (112).]

1a. Partial analysis of the portion of N1377 soluble in HCl.

2. Brown carbonatite from the 'dike' on Chigwakwalu Hill, Tundulu. M. H. Hey anal. [N1380, B.M. 1935, 1211 (115).]

2a. Partial analysis of the portion of N1380 soluble in HCl.

3. Sövite. Analysis of a 50-kg. sample taken from a dike on the shore of Nordsjö (Hydros Bruch), Fen district, Norway. L. Thomassen anal. (Brøgger, 1921: 243.)

4. Mixed feldspar-carbonate rock from Tundulu Hill, Southern Nyasaland. M. H. Hey anal. [N1185, B.M. 1933, 355 (46).]

4a. Partial analysis of the portion of N1185 soluble in HCl.

* Two different acid extractions.

† Confirmed by a second determination on a smaller sample.

In N1380 SrO is only half as much as in N1377 and is calculated as $SrCO_3$; the BaO is allotted to SO_3 for baryte, which is known to be present in the thin sections. P_2O_5 is low at 0·03 and is calculated as apatite. Cb_2O_5 0·30 per cent. corresponding to about 0·45 per cent. of pyrochlore, and the rare-earth oxides 0·4 per cent., wholly soluble, are referable to synchysite 0·75 per cent. The TiO_2 may be present mainly as rutile and the greater part of the Al_2O_3 and all the potash are allotted tentatively to feldspar. The high Fe_2O_3 and MnO are in conformity with the dark brown colouring of the rock and are doubtless present as oxides and hydrated oxides in the dark brown pseudomorphous carbonate. No fluorine was found in the carbonate. Feldspathic veins in the same specimen have F 0·05, P_2O_5 0·30, $(Cb,Ta)_2O_5$ nil.

As for N1377, it is difficult to completely correlate the chemical analysis and the composition in terms of minerals as at present identified.

A sample of this carbonatite was sent with others to Professor P. Baertschi for a determination of the $C^{13}:C^{12}$ ratio, and $O^{18}:O^{16}$ ratio. A very brief and provisional account of the results has been published in a letter (1951). Professor Baertschi notes that the 'intrusive' carbonatites have a very similar oxygen–18 abundance to that of magmatic oxygen. Similar investigations have been made on the carbonate-rocks of Alnö, Fen, and two other areas in Norway by H. von Eckermann, Ubisch, and Wickman (1952).

N1185 is a mixed carbonate-feldspar rock with feldspar making about 50 per cent. of the whole and carbonate acting as a cement to the breccia. A bulk analysis was made of the whole rock and a second analysis was made of the portion of the rock soluble in 2N HCl after treatment, as for the two other rocks, for 3 to 4 hours on a water-bath. The rock is described above (p. 110). The figures are given in Table I.

Calculation shows that feldspar, almost entirely potash-rich orthoclase, constitutes about 47 per cent. of the rock. Of the remainder Fe_2O_3 and MnO make up 11 per cent. (13·44 per cent. including H_2O), leaving only 40 per cent. for carbonate as calcite and the accessory minerals, pyrochlore, baryte, synchysite, apatite, and free quartz.

The rare-earth oxides are entirely soluble under the hydrochloric acid treatment and can be confidently referred to synchysite. The 0·2 per cent. corresponds to 0·46 per cent. synchysite in the whole feldspar-carbonate aggregate. If, as is probable, the synchysite is confined to the carbonate its proportion amounts to 1·15 per cent. This is higher than in the brown carbonate rock N1380. The content of columbium and tantalum oxides, 0·25, corresponds to 0·4 per cent. pyrochlore. If, like the synchysite, this were all confined to the carbonate, its proportion therein would be about 1 per cent. or 0·7 per cent. of the carbonate plus oxides. No pyrochlore could be seen in the feldspathic portion in the thin sections, nor was it actually identified in the carbonate under the microscope, but the carbonate portion of the rock is very dark and opaque and one might fail to identify pyrochlore in the thin sections.

COMPARISON WITH CARBONATITES FROM OTHER AREAS

As remarked in the Bulletin on the Chilwa Series (Dixey, 1937: 41), there is in a general way a similarity between the carbonate rocks of Chilwa and Tundulu and some of the carbonate rocks of the Fen district and of Alnö Island. One might class the Chilwa and Tundulu carbonatites with the purest of the sövites described by H. von Eckermann from Alnö, but no very close comparison can be made. Eckermann gives one analysis of a sövite in which the calcite is 96·9 per cent. and apatite only 2·5 per cent. In another the calcite amounts to 89·2 per cent., apatite 4·5 per cent., and biotite 6·2 per cent. The MgO content is 0·15 per cent. in the former and only 1·45 per cent. in the biotite-sövite. In this low MgO content in rocks with nearly 90 per cent. carbonate the Alnö sövites resemble the Chilwa carbonatites. In the three Chilwa rocks analysed MgO runs 0·31, 0·25, 0·23.

Apatite makes about 7·5 per cent. of the carbonate-rock N1377. This rock would on that account fall in von Eckermann's apatite-sövites, but it differs from these in containing no biotite, which is a constituent of many of the Alnö sövites. At Chilwa

and Tundulu biotite has been found only in the darker bands of the carbonate-rocks and in one biotite-rich type [N1297] from the summit of Chilwa Mountain.

Eckermann recorded knopite and pyrochlore in some sövite erratics (now all dispersed by collectors) on Stugholmen Island and in one of the sövite-breccia dikes between Smedsgarden and Stavsätt (1948: 69). At the last locality pyrochlore was associated with a pleochroic red mica assumed by A. G. Högbom to be manganophyllite but now known to have a quite low content of MnO.

Other rocks of very high calcite-content (and very low MgO) described by von Eckermann from Alnö occur as cone-sheets belonging to the group of rocks he has called alvikites (1948: 127, Pl. 42, Fig. 1, and analysis No. 120, p. 137). The alvikite of analysis 120 carries excess CO_2 believed to reside as such in cavities which the grinding of the sample did not open up. It is interesting to note that von Eckermann identifies some of the apatite in these rocks as carbonate-apatite on account of the fact that the crystals show sector twinning (1948: 127). He found free CO_2 also in some dolomitic carbonatite dikes (beforsites).

In the Fen district of Norway Brøgger described many sövites occurring both as dikes and as schlieren in the silicate rocks in which apatite ranges from 3 to 8 per cent. and mica from 2 to 8·5 per cent. Three of the analysed examples contain 0·80, 0·78, 0·82 per cent. $(Cb,Ta)_2O_5$, present in the rock as a member of the pyrochlore-microlite series (see p. 105). MgO in the Fen district sövites is higher than at Alnö, namely, 3·10, 2·83, 2·25 as against 0·15 and 1·45 in the Alnö sövites. As already noted, the Tundulu carbonate-rocks are lower still in MgO. It may also be noted in passing that the Tundulu brown carbonate-rocks are richer in BaO than any of the Fen or Alnö sövites analysed (Eckermann, 1950, 1952). An analysis of one of the Fen sövites is quoted in Table I.

In addition to the carbonatites with high percentages of calcite (the pure sövites) a few specimens have been collected both at Chilwa Island and at Tundulu which, in a general way, correspond to some of the mixed carbonate-silicate rocks variously named by Brøgger ringite, hollaite, and kåsenite.[1] These are N1271 and N1274*c* and *b* from Chilwa Island and DN7, DN13*a*, N1181, and N1195 from Tundulu. They have been briefly described above. One other comparison may perhaps be made. The peculiar biotite-calcite rock [N1297] from the crest of Mount Chilwa in some ways recalls the groundmass of the rock described by Brøgger as 'damkjernite', but it lacks the dominant pyroxene and characteristic inclusions.

At Alnö the carbonatites (sövites) form the central part of an area of fenitized Archaean rocks. The sövites of this central area form several islands and some shore outcrops and are supposed to have occupied an area some 2,000 metres across. They also form cone-sheets which appear as dikes. They are surrounded by various melanocratic alkaline rocks and these also are represented among radial dikes generally later than the cone-sheets. The present erosion surface is believed to be some 2,000 metres below the original top of the intrusions. Von Eckermann's opinion (1948) was that the alkaline rocks are believed to have been derived from a 'carbonatic magmatic liquid' rich in potash, magnesia, lime, carbon dioxide, and fluorine. Reaction of this

[1] H. von Eckermann refers to Brøgger's ringite, hollaite, and kåsenite as sövite with appropriate prefixing of mineral names: apatite-, pyroxene-, and biotite-.

liquid with the wall-rocks fenitized these and enriched the liquids with silicates, giving rise to the melanocratic alkaline rocks (by settling) and, at a lower temperature, to the liquids which develop into sövites, alvikites, and beforsites.

The Fen district described by W. C. Brøgger in 1921 was regarded by N. L. Bowen (1924) as an example of hydrothermal replacement of silicates by calcite and dolomite. A more recent study of the Fen rocks by E. Saether (1949) leads him to the conclusion (*fide* von Eckermann) that 'a primary basic magma, originally rich in carbonates, gives rise on solidifying to a residual magma exceedingly rich in carbonates and produces ultimately carbonatitic alkaline hydrothermal liquids'. 'Accordingly', writes von Eckermann (1952: 208), 'some soevite is taken to be magmatic, but the major part is considered to derive from hydrothermal metasomatic metamorphism of basic siliceous rocks'. The investigations of the isotopic composition of the carbon in the carbonatites carried out by von Eckermann, H. von Ubisch, and F. E. Wickman (1952), and by P. Baertschi (1951), as part of a wider inquiry, have thrown no certain light on the origin of these rocks.

In Bulletin No. 5 of the Nyasaland Geological Survey (1937: 40–41) the authors draw attention to the general resemblance of the Chilwa Series carbonatites with those of the Fen district and of Alnö, and also of a region near Cape Turja (Turij) in the Kola Peninsula described by D. Beliankin and V. Vlodavec in 1932. In recent years several of the carbonatite occurrences in Uganda, Kenya, Southern Rhodesia, and South Africa have been described or redescribed.

The mineralogy of some of these occurrences in Uganda in which apatite becomes of economic importance was described by K. A. Davies (1947), and a more complete account of the carbonate-rocks of the vent at Lokupoi in Southern Karamoja has been given by B. C. King (1949). Still more recently the present position and a statement of the evidence for and against four separate theories of the origin of the carbonatites has been summarized in the reply to the discussion on a paper on 'The alkali complex at Spitskop, Sekukuniland, Eastern Transvaal' by C. A. Strauss and F. C. Truter (1951: 130). The theory that the carbonatites are 'products of magmatic activity of a specific type' at present has the support of most of the petrologists who have studied the carbonatites in the field and in the laboratory.

Perhaps none of these other areas of carbonatites correspond very closely to the Mount Chilwa carbonatites and its associated feldspathic breccias, but the comparison with Alnö is in some respects impressive. One may perhaps compare the carbonatite mass of Mount Chilwa, 1½ miles across, with the 'central' area of sövite represented by the rocks of the islands of Sagholmen, Stugholmen, and the other smaller ones. If this is correct, then other vents in the Chilwa Series may represent similar carbonatite cores at independent centres.

Both at Alnö and Schelingen in Kaiserstuhl the minerals of the pyrochlore group are recorded only in the carbonate-rocks[1] of the central vents and dikes, associated in both areas with ijolitic and other alkali intrusive rocks. Von Eckermann thinks of the constituents of the pyrochlore as being carried up with the concentration of volatiles, CO_2, &c., that culminated in the 'sövite-explosion'. The

[1] In the Fen district Brøgger found pyrochlore ('microlite') in rocks of the ijolite-melteigite series (1921: 54).

conditions at Chilwa appear to be similar and the pyrochlore, so far as observations go up to the present, appears to be concentrated in the carbonatites and not in the surrounding fenites and alkali intrusives. Feldspathic veins in N1380 contain no $(Cb,Ta)_2O_5$.

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EXPLANATION OF PLATE

(*Photographs by Mr. D. L. Williams, Dept. of Mineralogy*)

FIG. 1. Pyrochlore (grey; left and top of field) and (black) opaque pseudomorphs probably after pyrite in carbonatite. [N1278, B.M. 1935, 1211(9)]. East end of south spur, Chilwa Island. × 20. (See pp. 104 and 108.)

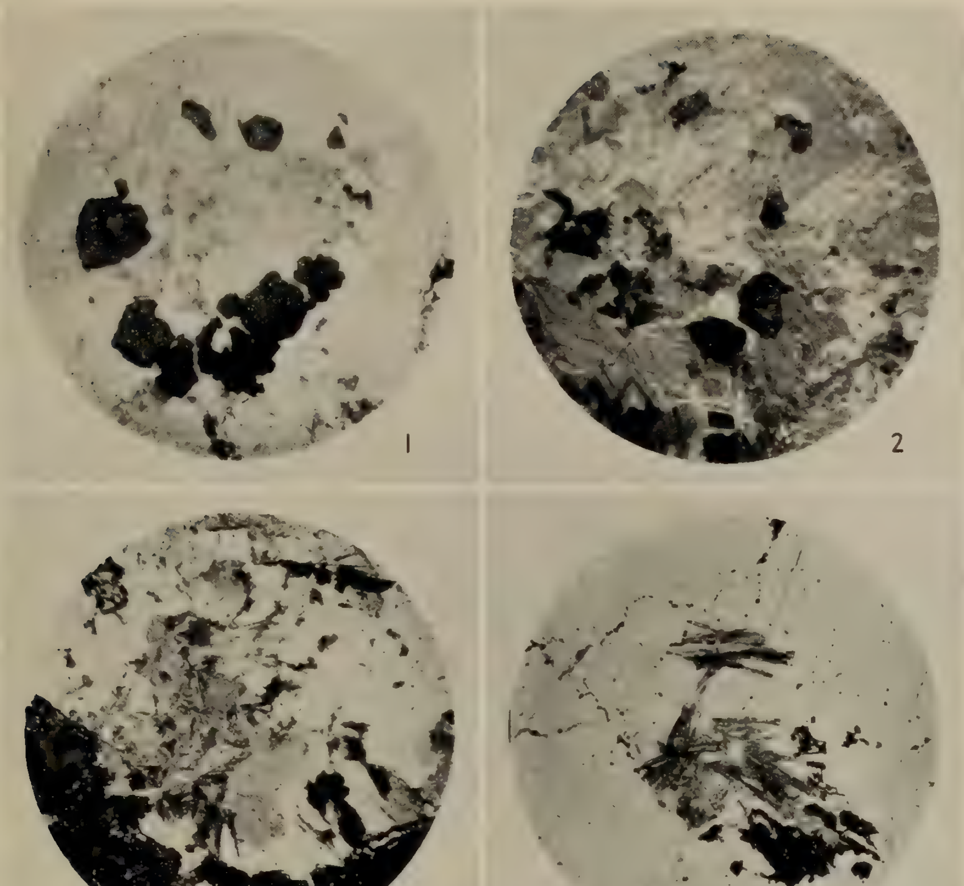
FIG. 2. Pseudomorphs, opaque, rhombohedral, after chalybite, in calcite plates. [N1378, B.M. 1935, 1211(113).] From the 'dike' on Chigwakwalu Hill, Tundulu. × 20. (See pp. 104 and 111.)

FIG. 3. Synchysite blades in mottled calcite. [DN8*d*]. Western foot of central cone, Tundulu Hill. Crossed polaroids. × 20. (See p. 112.)

FIG. 4. Synchysite blades in drusy cavity in carbonatite. [N1189*a*, B.M. 1934,131(5)]. Tundulu Hill. × 44. (See pp. 105 and 110.)

FIG. 5. Inclusions of transparent colourless rhombs in calcite plates. [N1189*a*, B.M. 1934,131(5)]. Tundulu Hill. × 240. (See pp. 103 and 110.)

FIG. 6. Pseudomorphs of a mineral of acicular habit in calcite. A band rich in ovate grains of apatite occupies the lower part of the field. [N1273, B.M. 1935,1211(5)]. × 44. (See pp. 104 and 108.)



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